

Baryon/anti-baryon inhomogeneity and big bang nucleosynthesis

Kevork Abazajian and George M. Fuller ^a

^a*Department of Physics, University of California, San Diego,
La Jolla, California 92109-0319*

Abstract. We investigate the effects of baryon/anti-baryon inhomogeneity on primordial nucleosynthesis. Recent work claims that electroweak baryogenesis could give rise to distinct regions of net baryon and anti-baryon number, which could survive until the nucleosynthesis epoch. We discuss neutron diffusion effects on nucleosynthesis yields in these models and speculate on the prospects for obtaining constraints.

1. Introduction

Big bang nucleosynthesis (BBN) has been one of the most successful enterprises of modern cosmology. Comparison of observationally inferred primordial light element abundances with predictions from theoretical BBN calculations provide strong constraints on conditions of the Early Universe. The Early Universe somehow must either produce the simple and appealing homogeneous conditions of the standard BBN model, or it must produce an exceptional set of inhomogeneous conditions that generate the observed light element abundances. Prompted by work on the QCD phase transition, the effect of high-amplitude, sub-horizon scale, baryon-number fluctuations on BBN were studied [1–3]. A detailed numerical calculation of the evolution of such inhomogeneities through nucleosynthesis was done by Jedamzik, Fuller, and Mathews [4]. Neutrino-, baryon-, and photon-induced dissipative processes were coupled to nuclear reaction rates in multiple regions in an extension of the standard Wagoner [5] nucleosynthesis code. In Ref. [4], it was found that any significant inhomogeneities overproduced helium-4 and/or deuterium. The effect of a first-order electroweak transition that produced similar baryon-number inhomogeneities has also been studied [6].

Recently, Giovannini and Shaposhnikov [7] have suggested that electroweak baryogenesis could take place through baryon-number-violating interactions with a primordial (hyper-)magnetic field. The primordial field could fluctuate across regions much larger than the horizon at the electroweak epoch, and also could cause both positive and negative baryon-number fluctuations. This could leave baryon/anti-baryon homogeneities that conceivably could survive until the BBN epoch. In Ref. [7], constraints were placed on the fields that guaranteed that they would have no effect on standard BBN. That is, the baryon/anti-baryon regions were constructed to be smaller than the baryon diffusion length at the epoch of BBN, so that such regions were

damped out early. These fluctuations were constructed so that the weak interactions reset the resulting neutron-to-proton ratio, n/p , to its standard BBN value.

The n/p ratio is extremely important in determining the resulting element abundances. Since almost all neutrons are eventually incorporated into alpha particles, any change in the n/p ratio will affect the ^4He abundance. Roughly, the mass fraction, Y_p , of ^4He will be

$$Y_p \approx \frac{4n_4}{n_n + n_p} = \frac{2(n/p)}{(n/p)} \approx 1/4. \quad (1)$$

Baryon/anti-baryon regions that are larger than the baryon diffusion length could significantly affect the n/p ratio. Rehm and Jedamzik [8] have recently studied these issues.

2. Nucleosynthesis with baryon/anti-baryon inhomogeneities

Baryon and anti-baryon regions that survive until the neutron-proton weak interaction freeze-out epoch subsequently will face neutron/antineutron diffusion and, therefore, baryon/anti-baryon annihilation. Ultimately, that which we call “matter” must win out in annihilations and thus must have a greater net number than antimatter. Weak freeze-out occurs at a temperature $T_{WFO} \sim 1$ MeV when neutrons and protons (and their antiparticles) cease to be rapidly interconverted one to another by lepton capture processes. Separate regions of baryons or anti-baryons will be preserved for epochs $T > T_{WFO}$ if the length scales associated with these fluctuations are large compared to the baryon (anti-baryon) diffusion length. However for $T < T_{WFO}$, neutrons and antineutrons will diffuse efficiently between these regions, while protons and antiprotons remain relatively fixed in their respective regions because of coulomb interactions with the e^\pm background. Neutrons and antineutrons are free from such interactions and their diffusion length is several orders of magnitude larger. Neutrons “free stream” into anti-baryon regions, and antineutrons “free stream” out into the baryon regions. Assuming the baryon regions are significantly larger (in total number of baryons), annihilations between neutrons and anti-baryons in the former anti-baryon regions have two important effects: (1) depletion of neutrons in the baryon regions, and (2) the formation of extremely neutron-rich “bubbles” in place of the anti-baryon regions.

Recent work on the observationally inferred primordial abundances of the light elements D, ^4He , and ^7Li have left a slight, yet significant disparity between the predicted standard BBN abundances and measurements [9–11]. Observationally inferred abundances and corresponding BBN-inferred baryon-to-photon ratios (η ’s) are: $Y_p = 0.234 \pm 0.002$, $\eta_{\text{He}} = (1.8 \pm 0.3) \times 10^{-10}$; $\text{D}/\text{H} = (3.4 \pm 0.3 \pm 0.3) \times 10^{-5}$, $\eta_{\text{D}} = (5.1 \pm 0.3) \times 10^{-10}$; $^7\text{Li}/\text{H} = (3.2 \pm 0.12 \pm 0.05) \times 10^{-10}$, $\eta_{\text{Li}} = (1.7_{-0.3}^{+0.5}) \times 10^{-10}$ or $(4.0_{-0.9}^{+0.8}) \times 10^{-10}$. Specifically, the production of ^4He is inconsistent (too high) with the η inferred from the primordial deuterium abundance.

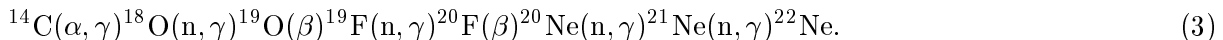
Neutron-depleted baryon regions and the neutron bubbles have interesting consequences for BBN. The depletion of neutrons lowers the n/p ratio and, therefore, lowers the predicted ^4He abundance. We can show that the number density, $n_{\bar{b}}$, of the anti-baryon regions that occupy a fraction of the horizon volume, f_v , is related to the number density of the baryons, n_b , in the baryon regions by

$$n_{\bar{b}} = \left[\frac{k_{\text{NSE}}(1 - f_v) - k_{\text{He}}}{f_v(1 - f_v + k_{\text{He}})} \right] n_b. \quad (2)$$

Here, k_{NSE} is the standard BBN n/p ratio, and k_{He} is the n/p ratio that corresponds to the observed ${}^4\text{He}$ abundance. The number densities n_b and $n_{\bar{b}}$ refer to the epoch just prior to T_{WFO} . If the initial number density of the anti-baryon regions is equal to the number density of the baryon regions, then the fractional volume that can be occupied by anti-baryons for concordance between ${}^4\text{He}$ and observationally inferred deuterium abundance is $f_v = 10^{-4}$. This small fraction reflects the small order of disparity between the light element abundances. Anti-baryon regions with slightly larger f_v will underproduce ${}^4\text{He}$; anti-baryon regions with significantly larger f_v will not have all of their anti-baryons annihilated prior to nucleosynthesis.

Nucleosynthesis in the neutron-rich regions is also important when considering baryon and anti-baryon inhomogeneities. In order to simulate nucleosynthesis in these regions, we have forced the weak interactions rates to freeze-out the n/p ratio at ~ 6 and ~ 10 . The “isospin symmetric” nucleosynthesis of $n/p \sim 6$ would be expected to evolve identically to the standard case of $n/p \sim 1/6$, with nucleosynthesis being limited by the lack of protons rather than neutrons. However, the decay of neutrons provides a source for protons in these neutron-rich regions and can lead to unique nucleosynthesis results. In our numerical calculations, the production of beryllium-9 and boron-11 become significantly amplified. The recent limits on the abundance of these elements in low metallicity stars provide a strong upper bound on their primordial production [12,13].

We have also included reactions leading to heavier element production in neutron-rich regions:



Through further (n, γ) reactions and β -decays, the products of these reactions may trigger the r-process in the neutron-rich bubbles. Primordial production of heavy elements is also constrained by older Population II stars. However, a limited primordial source of heavy elements can not be ruled out.

Whether or not values of the parameters n_b , $n_{\bar{b}}$, and f_v exist for which all of the nucleosynthesis constraints can be met remains an open question. It appears to us, however, that it will be extremely difficult to find such values, especially in light of potential B, Be, and r-process production in these schemes.

3. Acknowledgment

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